TITLE
ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Jodrell Bank Timing Astrometry

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Abstract. More than 500 pulsars are regularly observed with the 76-m Lovell radio telescope at Jodrell Bank Observatory. Precise positional and rotational parameters have been obtained from observations spanning between 6 and 34 years for over 300 of these pulsars. The parameters were determined by fitting a timing model to whitened pulse arrival times. In this paper, the technique used to whiten the timing residuals is summarised and the astrometric measurements are compared to proper motions determined earlier with interferometers. This novel approach has led to the first proper motion measurements for 111 pulsars and improved results for 15 pulsars.

1. Introduction

For pulsars with significant timing noise, proper motion measurements have traditionally been obtained using interferometers such as the VLA, VLBI or MERLIN (for example, Brisken 2001; Lyne, Anderson & Salter 1982 and Harrison, Lyne & Anderson 1993). We show here that timing observations can provide a simple method for obtaining the proper motions of a large number of pulsars. These results agree well with published values if timing noise is correctly removed from the pulsars' timing residuals. The astrophysics obtainable from such a large sample of proper motion measurements is manyfold. For example, the birth velocities may arise due to asymmetric supernovae. The pulsar velocities are, in many cases, greater than the escape velocities of binary systems, globular clusters and the Galaxy. The isotropic distribution of pulsars in the Milky Way may be distributed in a fashion similar to the sources producing γ-ray bursts and tracing a pulsar's position back in time can lead to new supernova remnant associations.

More than 500 pulsars are regularly observed using the 76-m Lovell radio telescope at Jodrell Bank observatory. For each observation, folded pulse profiles, two orthogonal polarizations and a time stamp are recorded. Observations have been made predominately at frequencies close to 408, 610, 910, 1410 or 1630 MHz. During standard observing procedures, the signals of each polarization are mixed to an intermediate frequency, fed through a multi–channel

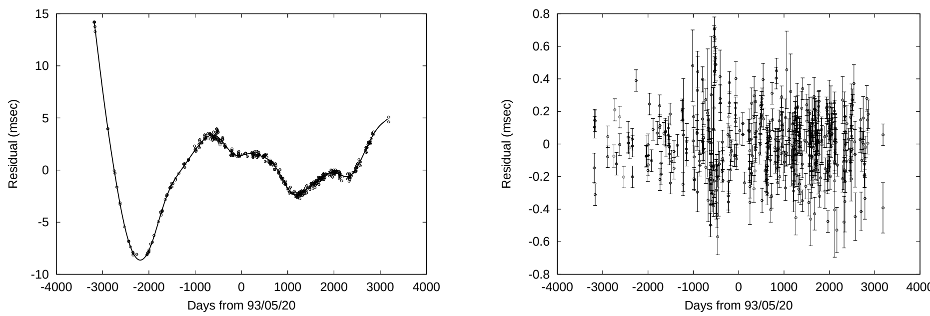

Figure 1. The timing residuals for PSR B0450−18, (a) pre- and (b) post- whitening.

filterbank and digitized. The data are dedispersed in hardware, folded on–line according to the pulsar's dispersion measure and topocentric period and the polarizations added. Pulse times–of–arrivals (TOAs) are subsequently determined by convolving the averaged profile with a template of high S/N corresponding to the observing frequency. The TOAs are corrected to the solar system barycentre using the Jet Propulsion Laboratory DE200 solar system ephemeris (Standish 1982).

2. FITWAVES

The rotational and astrometric parameters for each pulsar are obtained by model–fitting the TOAs using TEMPO[1]. A proper motion leads to a sinusoid, in the timing residuals, with a period of one year and an amplitude that increases linearly with time. However, the timing residuals for many pulsars contain timing noise, a continuous, noise like fluctuation in rotation rate, which must be removed before fitting the timing model. This removal, or whitening of the data, has traditionally been carried out by removing polynomials from the timing residuals. However, with this method, the proper motion signature can be affected due to the lack of control over the frequency range of the timing noise spectrum being removed from the timing residuals.

A method, known as FITWAVES, to whiten timing residuals has been developed that fits harmonically related sinusoids to the timing residuals. The number of harmonics used is determined by the period of the shortest structure required to be removed from the timing residuals. Therefore, FITWAVES can remove long–period timing noise without affecting the proper motion signature. Figure 1 shows the technique being applied to the timing residuals of PSR B0450−18. After fitting to the pulse TOAs for rotational period and its first two derivatives, the residuals have the form shown in Figure 1a. The curve fitted through the points has been obtained by fitting thirteen harmoni-

[1] see http://pulsar.princeton.edu/tempo

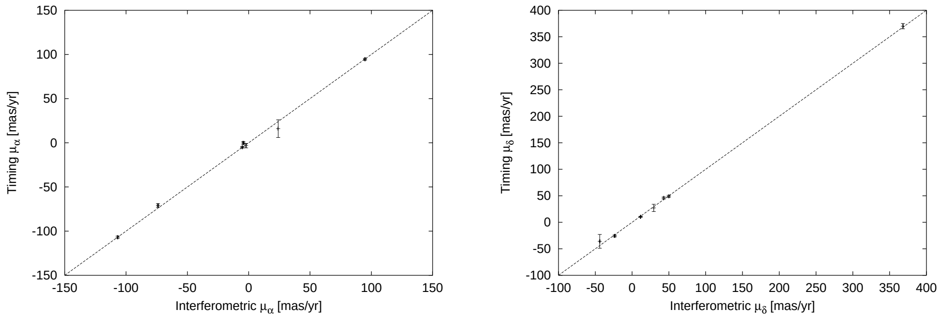

Figure 2. The timing results obtained using the method described here compared to the interferometric results of Brisken (2001).

cally related sines and cosines to these residuals. Whitened timing residuals are formed by removing this curve from the original residuals (Figure 1b). With these whitened residuals, it is possible to determine the pulsar's proper motion in right ascension, $\mu_\alpha = 11(2)\,\mathrm{mas\,yr^{-1}}$, and declination, $\mu_\delta = 6(4)\,\mathrm{mas\,yr^{-1}}$ which can be compared to interferometric measurements of $\mu_\alpha = 12(8)$ and $\mu_\delta = 18(15)\,\mathrm{mas\,yr^{-1}}$ published in Fomalont et al (1997).

2.1. Comparison of proper motions

Pulsar astrometric parameters were determined for 321 pulsars that have been observed for more than six years and have no history of glitching. The pulsars' positions, proper motions, dispersion measures and derivatives were determined by fitting a timing model to the whitened TOAs using TEMPO. The data were whitened using the FITWAVES method in such a way that timing noise features with periods greater than 1.5 years were removed leaving any remaining structure unchanged.

The proper motions for a large sample of pulsars have been tabulated in Hobbs et al. (2002) and will be described in detail in a subsequent paper (Hobbs et al. in preparation). This work has improved the precision to which 15 proper motions have been measured and has obtained the first proper motion results for 111 pulsars providing a sample of over 200 pulsars with measured proper motions. Here we show that the results being obtained for pulsars, whose timing residuals contain timing noise, agree with interferometric results.

The most precise pulsar proper motions have been obtained by Brisken (2001) using the VLBA. Figure 2 compares seven pulsars that were included in both analyses. These results are clearly consistent.

Earlier interferometric proper motions have been published using the VLA (Brisken 2001; Fomalont et al. 1997) and the MERLIN arrays (Lyne, Anderson & Salter 1982; Harrison, Lyne & Anderson 1993). The most precise interferometric results from these publications are compared, in Figure 3, to the proper motions acquired using the timing method. Although an inconsistency exists for the $\mu_\delta = -98(6)\,\mathrm{mas\,yr^{-1}}$ measurement of PSR B0906−17 compared to

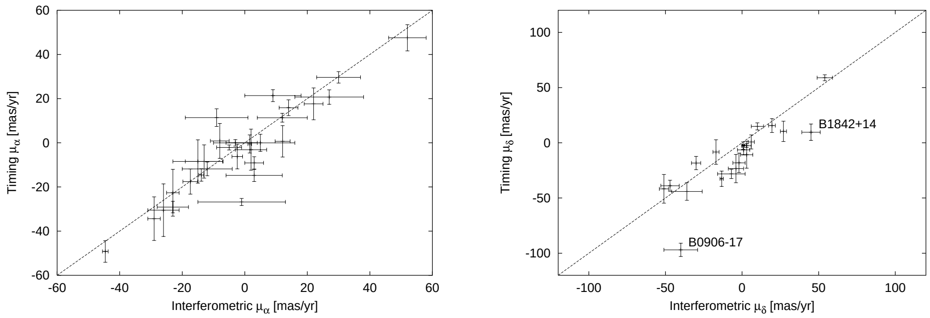

Figure 3. The proper motions in right ascension (μ_α) and declination (μ_δ) obtained using the method described here to the MERLIN or VLA interferometric results.

$-40(11)\,\mathrm{mas\,yr^{-1}}$ in Harrison, Lyne & Anderson (1993), the majority of the proper motions are consistent with earlier results.

3. Conclusion

Pulsars' rotational and astrometric parameters can be obtained from whitened timing residuals. The timing noise present in the timing residuals can be removed by fitting harmonically related sinusoids to the data. The astrometric parameters obtained from this timing method agree with those measured using interferometers, even if timing noise is present in the original non-whitened timing residuals. Applying this technique to all the pulsar residuals stored in the Jodrell Bank data archive has led to more than 100 new proper motions (and hence pulsar velocities) being measured.

References

Brisken, W. F., 2001, PhD thesis, Princeton University

Fomalont, E. B., Goss, W. M., Manchester, R. N., Lyne, A. G., 1997, MNRAS, 286, 81

Harrison, P. A., Lyne, A. G., & Anderson, B., 1993, MNRAS, 261, 113

Hobbs, G., 2002, PhD thesis, University of Manchester (submitted)

Lyne, A. G., Anderson, B., & Salter, M. J., 1982, MNRAS, 201, 503

Standish, E. M., 1982, A&A, 114, 297

Toscano, M., Sandhu, J. S., Bailes, M., Manchester, R. N., Britton, M. C., Kulkarni, S. R., Anderson, S. B., & Stappers, B. W., 1999, MNRAS, 307, 925